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HIGH-ENERGY IONS IN LASER-PLASMA INTERACTIONS.(U)

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NRL Memorandum Report 3577

High-Energy Ions in Laser-Plasma Interactions

R. DECOSTE and B. H. RIPIN

Laser Plasma Branch
Plasma Physics Division

October 1977

NAVAL RESEARCH LABORATORY
Washington, D.C.

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: ~~NRL Memorandum Report 3577~~ 2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle): (6) HIGH-ENERGY IONS IN LASER-PLASMA INTERACTIONS,	5. TYPE OF REPORT & PERIOD COVERED: Interim report on a continuing NRL problem.
	6. PERFORMING ORG. REPORT NUMBER: (14) NRL-MR-3577
7. AUTHOR(s): (10) R. Decoste* ~~and~~ B.H. Ripin	8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Naval Research Laboratory, Washington, D.C. 20375	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: NRL Problem H02-29A
11. CONTROLLING OFFICE NAME AND ADDRESS: Energy Research and Development Admin. Washington, D.C. 20545	12. REPORT DATE: (11) Oct[redacted]77
	13. NUMBER OF PAGES: (12) 13 p.
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): (18) SBIE (19) AD-E000 051	15. SECURITY CLASS. (of this report): UNCLASSIFIED
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

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This research was performed at NRL under the auspices of the U.S. Energy Research and Development Admin.
Decoste was partially supported by a Hydro-Quebec fellowship (Can.).

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Ion expansion
Hydrodynamic
Hot plasma
Ion energy

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A two-ion fluid, 1-D model is proposed to explain some features of the high energy ion distributions recently measured in laser-plasma interaction. The model describes the ambipolar expansion of hot electrons and two relatively cold ion species from a pressure gradient. The model accounts for the energy and relative behavior of high-energy ion species measured experimentally.

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S/N 0102-014-6601

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

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HIGH-ENERGY IONS IN LASER-PLASMA INTERACTIONS

Historically, the high energy ions in a laser produced plasma are defined as a small group of ions transporting a significant fraction of the absorbed laser energy. Most expansion models[1,2] suggest that the high energy ions are the direct consequence of the expansion of the high energy electrons. However, these models have only considered the acceleration of a single ion species. Some recent measurements[3,4] of the asymptotic energy distribution of high energy ions from a multi-ion species plasma (CH_2) suggest that the relative behavior of the different ions species might lead to further information about the expansion and the acceleration mechanism of the ions. In our model, we therefore consider the ambipolar expansion of hot electrons with two relatively cold ion species from a pressure gradient. We will then show by comparison with experiments that such a pressure gradient model can account for the energy and the relative behavior of these high energy ion species.

A typical energy distribution of the high energy ions measured from a Nd-laser target irradiation is shown in Fig. 1. Mutlipeak structure on the H^+(hydrogen) ion energy distribution has been observed between 10 and 100 keV.[3,4] The group of H^+ ions with E/Z (energy divided by the charge) higher than the C (carbon) ions transports as much energy as the whole C ion group. The presence of C^{+5} and C^{+4}

Note: Manuscript submitted September 21, 1977.

ions at almost the same energy as the C^{+6} ions is consistent with some atomic processes, such as recombination or charge exchange, occurring during the expansion. We will therefore assume, in the model discussed below, that all the C ions were fully stripped during the acceleration phase of the expansion. A detailed discussion of these observations can be found elsewhere.[3] In this paper, we will concentrate mostly on the energy partition between H^+ and C^{+6} ions and show that it is consistent with a pressure gradient accelerating two different ion species.

The 1-D plasma is modeled using one hot electron background and two relatively cold ion fluids. The ion density profiles for our initial value problem are shown in Fig. 2a (dashed lines). Both density profiles have initially the same exponential scale length and a velocity negligible with respect to the final velocities.

The three species, one electron and two ion, are described by a standard set of conservation equations. Each ion fluid satisfies a continuity equation

$$\frac{\partial n_i}{\partial t} + \frac{\partial}{\partial x} n_i u_i = 0 \quad , \tag{1}$$

where $i = 1,2$. The momentum equation for the hot electrons is

$$0 = e\, n_e \frac{\partial}{\partial x} \phi - \frac{\partial}{\partial x} p_e \quad , \tag{2}$$

where ϕ is the ambipolar potential and $p_e = n_e k T_e$, the electron pressure. The momentum equation for both ion fluids is

$$m_i \frac{\partial}{\partial t} n_i u_i + m_i \frac{\partial}{\partial t} n_i u_i u_i = - Z_i e n_i \frac{\partial \phi}{\partial x} . \qquad (3)$$

We also assume that the density gradient scale length ℓ is much greater than the electron Debye length and, therefore, replace the Poisson equation for the ambipolar potential by a quasi-neutrality condition $n_e = Z_1 n_1 + Z_2 n_2$.

No collisional effects have been included in this model. The electron-ion collisions can be neglected due to the high electron temperature. An initial ion temperature[5] of a few hundred eV also makes the viscosity term ($\propto T_i^{-\frac{3}{2}}$) negligible with respect to the electric field in Eq. 3.[6,7] The ion temperature, although high enough to neglect viscosity, remains relatively small compared to the electron temperature, so that the ion pressure can also be neglected. The only interaction between the two ion species is then through the self-consistent electric field in Eq. 3.

An assumption about the electron temperature and the heat flow is required to close the moment equations. We assume a uniform electron temperature throughout the expansion region, i.e., the heat is allowed to flow without inhibition. The left boundary in Fig. 2a is an impenetrable wall with $u_i = 0$, $\partial p_e/\partial x = 0$ and no heat is allowed to flow across that boundary. The total energy is then conserved by reducing the electron temperature according to the rate of change of ion kinetic energy.

Equations 1 to 3 have been self-consistently solved numerically with the quasineutrality and energy conservation conditions using an

FCT algorithm[8] on a sliding-zone grid. Figure 2a shows the evolution of the ion density profiles for a CH_2 plasma after 3.6 τ (where τ is the density gradient scale length divided by the ion sound speed). As discussed above, all the C ions are assumed to be completely ionized. Because of the more rapid H^+ ion expansion relative to C^{+6} ions a bump has developed on the H^+ density profile. From Fig. 2b-c, one sees that this H^+ group transports an important fraction of the ion expansion energy at an energy about three times the initial electron temperature. In fact, most of the ion expansion energy is contained in a small fraction of the ions with energies higher than the initial electron temperature.

About 75% (Fig. 2c) of the electron thermal energy remains after 3.6 τ but, because of the much weaker density gradient, the ion acceleration by the ambipolar electric field is greatly reduced. The remaining thermal energy will then be dissipated via other channels, such as heat transport toward the overdense region and ion heating with eventual acceleration of slower ions.

The energy partition between the H^+ and the C^{+6} ions can also be predicted from the momentum equation (Eq. 3). For both ion species, the rate of change of ion kinetic energy ($E_i = \frac{1}{2} m_i v_i^2$) is initially given by (from Eq. 3)

$$\frac{d}{dt} E_i = \frac{Z_i^2}{A_i} \frac{e^2}{m_p} \epsilon^2 t \qquad (4)$$

where A_i and Z_i are respectively the ion atomic number and charge state and ϵ is the ambipolar electric field. Since most of the ion acceleration occurs before the separation of the species, the electric field and the ion acceleration time are essentially the <u>same</u> for both ion species. Therefore, Eq. 4 yields the following relation for the energy of the ion species.

$$\frac{E_i}{Z_i}\left(\frac{A_i}{Z_i}\right) = \text{const.} \qquad (5)$$

A different scaling, E_i/Z_i = const., would be valid only if the different ion species are accelerated through the same electrostatic potential for <u>different</u> acceleration times. From Eq. 5 a C^{+6} ion is then expected to have only three times more energy than a H^+ ion and a CH_2 target should yield 1.5 times more energy into the C^{+6} ions than the H^+ ions. Figure 2c shows, however, a C^{+6} to H^+ ion energy ratio close to 1.2. The extra energy (20%) found in the H^+ ions from the simulation is caused by different expansion velocities of the two ion species. The H^+ ions, because of their higher velocity, can take advantage of the pressure gradient set up by the slower C^{+6} ions. Nonetheless, the rate equation (Eq. 4), $\propto Z^2/A$, remains what basically determines the energy of the fast ions.

As mentioned above, we assume at 3.6 τ that the acceleration phase of the ion expansion is terminated and then calculate the asymptotic energy distribution for both ion species. The result is shown in Fig. 3a assuming an initial electron temperature of 22.5 keV.

Figure 3b shows the experimental energy distribution deduced from Fig. 1. Again the partial current of C^{+5} and C^{+4} were assumed to be C^{+6} during the acceleration phase. The 22.5 keV initial electron temperature was chosen to fit the H^+ peak from the expansion model to the high energy H^+ peak from the experiment. As can be seen in Fig. 3b, the experiment produces a higher ratio of H^+ to C ions than expected from a CH_2 target over the energy range considered.[9] This is, however, in qualitative agreement with the expansion model. The expansion energy was shared almost equally in the expansion model between H^+ and C^{+6} ions. Within experimental uncertainties this result is also consistent with the experiment.

A typical ion acceleration time scale for an initial electron temperature of $\sim$ 20 keV and scale length of a few microns is a few tens of picoseconds. The relatively high electron temperature required to explain the data has then to be maintained for only a short time and is therefore a peak temperature. Such a high temperature is indeed consistent with simulations using an artificially inhibited thermal conductivity[1] or including self-generated magnetic fields.[6,10] A different approach would have been to use a two electron temperature model with hot electrons controlling the ambipolar expansion of the ions.[11]

Our expansion model does not address the observation of the multi-peak structure of the H^+ ion distribution. This feature could be due to spatial or temporal variation of the pressure gradient. The high energy tail of the asymptotic high energy ion distribution can also

be treated with an approach different from that of the expansion model suggested above (vacuum interface problem).[12,13]

In summary, the electron pressure gradient model can account for the energy and the relative behavior of high energy ion species. In the context of a multi-species plasma expansion we have also shown that the rate of change of ion expansion energy ($\propto Z^2/A$) determines the energy partition among the fast ions. A further test of this model will then be to compare the asymptotic energy distribution from a CD_2 target to that from a CH_2 target. According to the Z^2/A scaling law, the D^+ ions should transport 6 times less energy per ion than the C^{+6} ions.

The authors wish to thank S. E. Bodner, H. R. Griem, and F. S. Felber for their interesting comments on this work and D. G. Colombant for his valuable assistance in the numerical calculations.

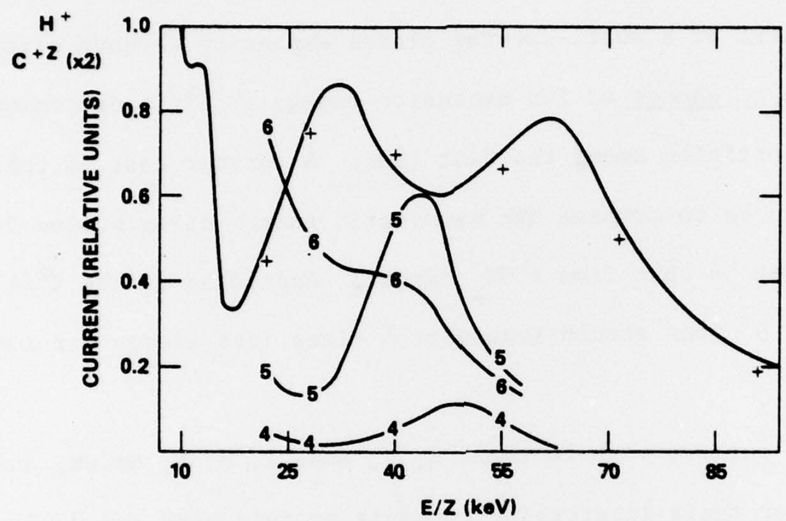

Fig. 1 - High-energy ion current distribution vs energy per unit charge. The numbers represent the Z of C^{+z} ions and + the H^+ ions. Laser parameters: 5×10^{15} W/cm^2 at 1.06 μm on a planar CH_2 target.

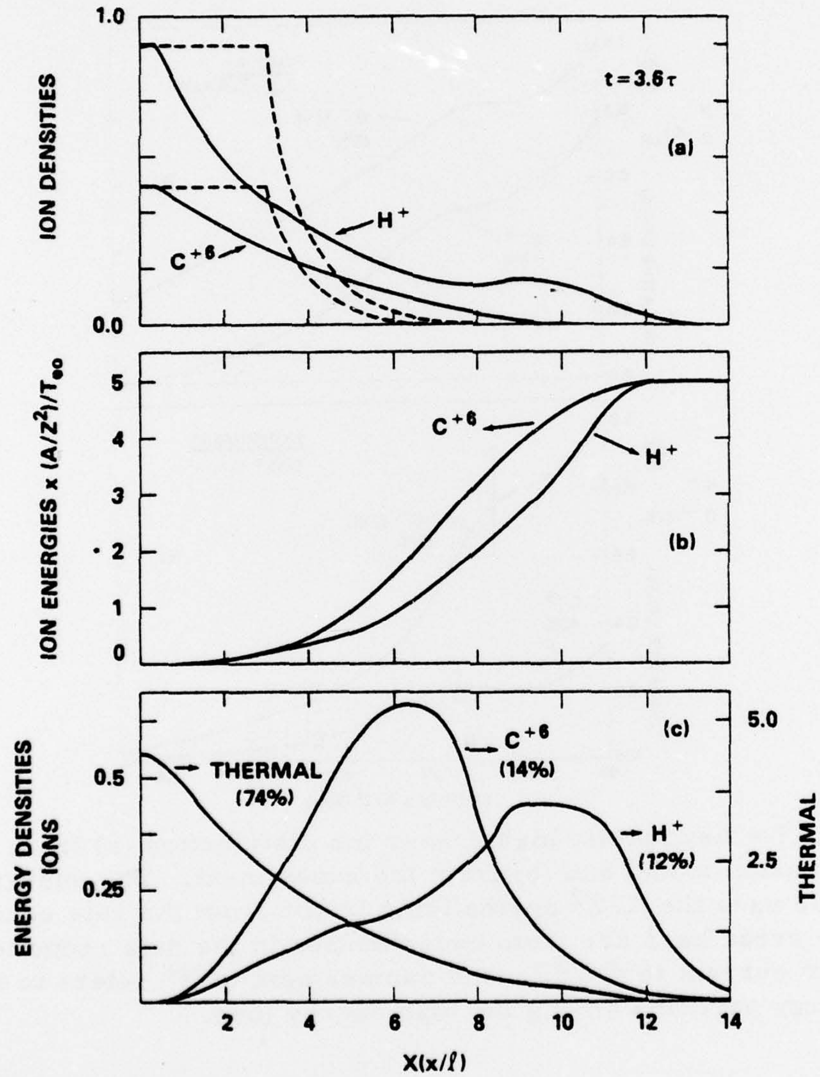

Fig. 2 - Ion densities, ion energies and energy densities versus distance at t = 3.6 . The dashed lines represent the initial density profiles. The ion densities are normalized to the initial H^+ plateau density. The non-dimensional units are: $\tau = \ell/c_s$, $c_s = (kT_{eo}/m_p)^{1/2}$, where T_{eo} is the initial electron temperature and ℓ the initial density gradient scale length. The percentages in parenthesis gives the energy partition.

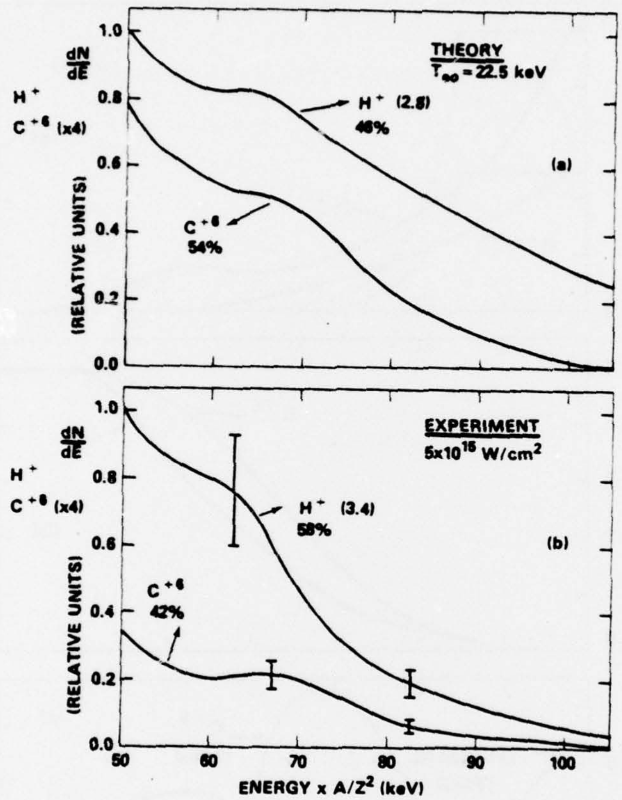

Fig. 3 - Asymptotic high energy ion distribution (a) from the expansion model and (b) from the experiment. The energy scale uses the A/Z^2 normalizing factor from the rate equation. The error bars are from uncertainties in the data reduction from current to dN/dE. the number next to H^+ refers to the energy partition among the high energy ions.

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